Developing an Optical Phased Array for the Breakthrough Starshot propulsion system

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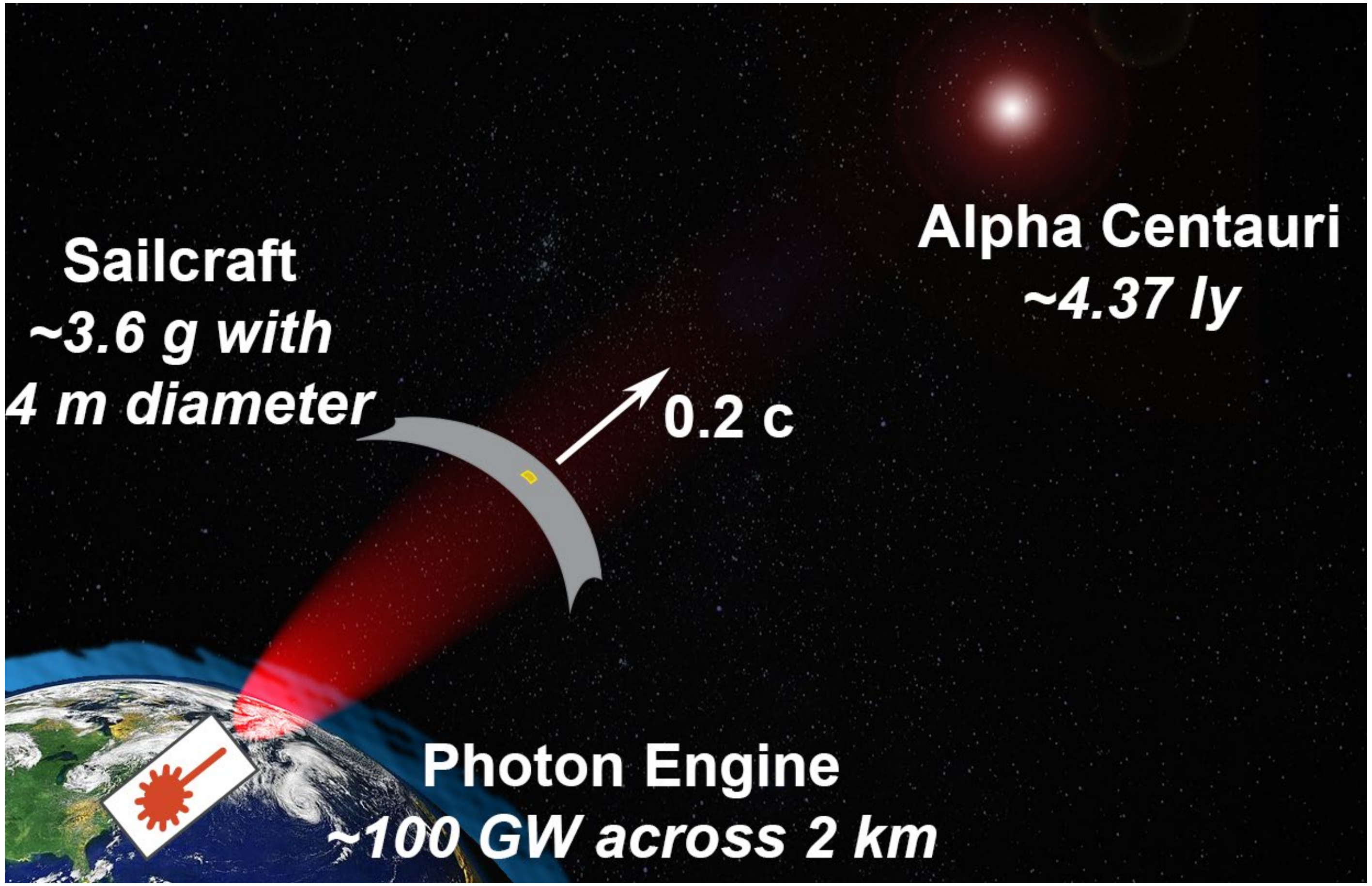
Research School of Astronomy and Astrophysics, ANU

Australian National University

AML Applied Metrology Labs

Breakthrough Starshot – at a glance



Photon Pressure

~3.6g (Initial proposed sailcraft weight)

10 minute illumination

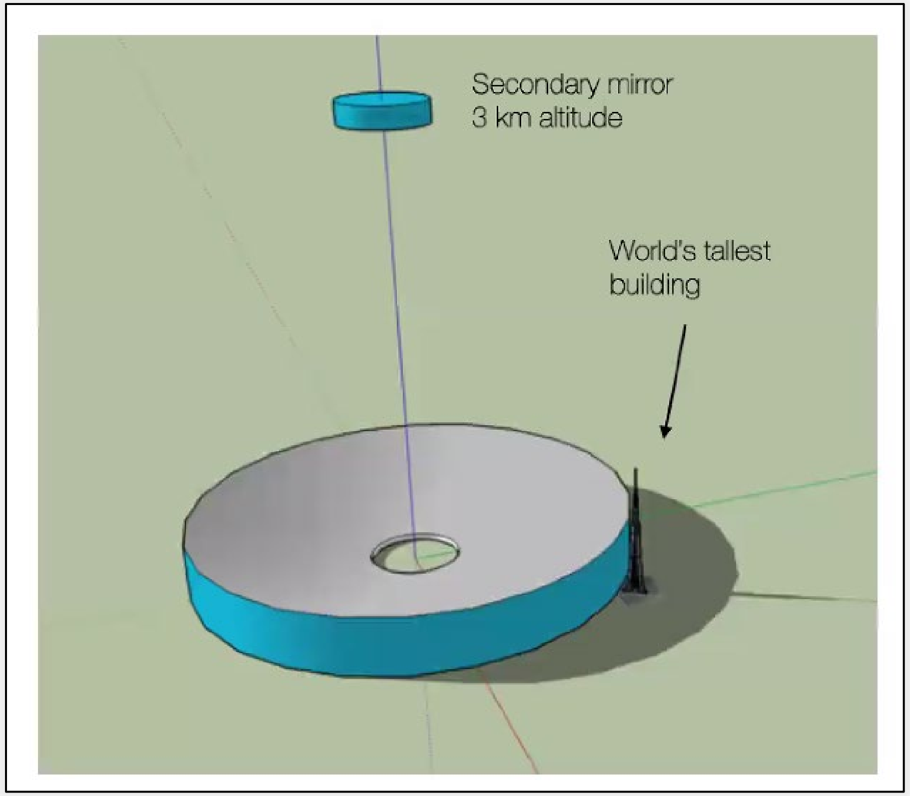
10mW	*→ 6um/s*
1kW	*→ 2km/hr*
100GW	*→~20% speed of light*
68 MW	*→40km/s (~Voyager speed)*

$$v_{sc} = \frac{LaserPower \cdot Time}{Mass \cdot c}$$

Parkin, K.L.G., *The Breakthrough Starshot system model. Acta Astronautica, 2018.* 152: p. 370-384.

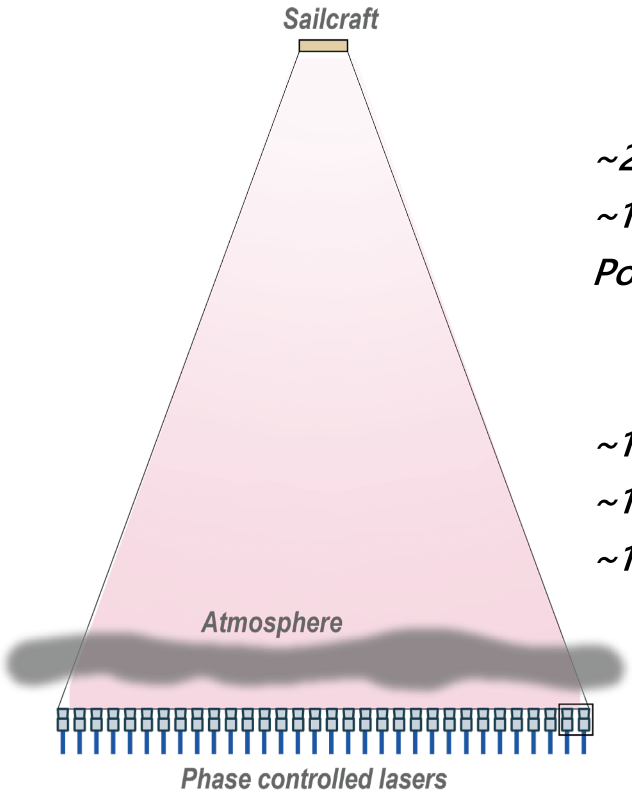
Breakthrough Starshot – Optical phased array

A conventional telescope approach



"What it can't be"
Breakthrough Starshot Communications Workshop

Optical phased array



Requirements (Estimated)

~2.8km Diameter

~100GW Power

Power on sailcraft throughout launch

Array parameters

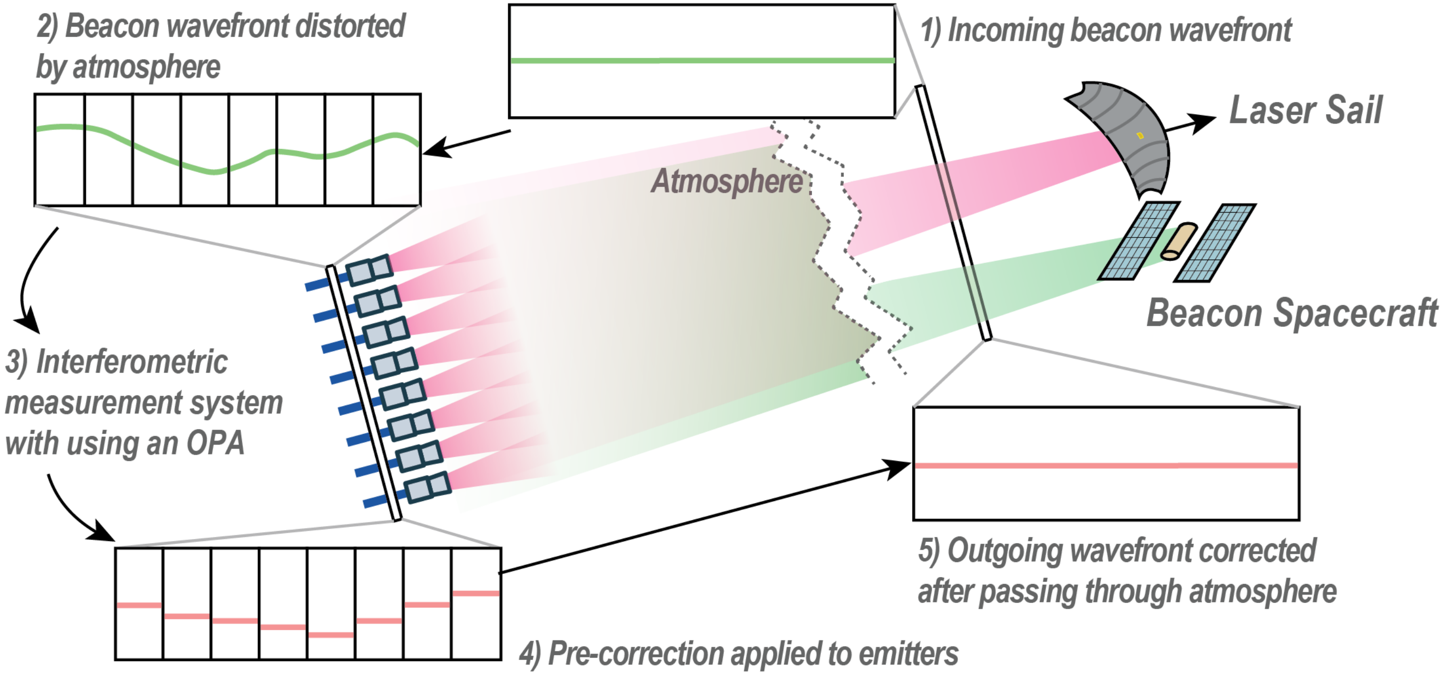
~100M : Emitters

~10cm : Apertures

~1kW : Per Emitter

Synthesize a large aperture telescope with phase controllable apertures

Cooperative interferometric sensing approach

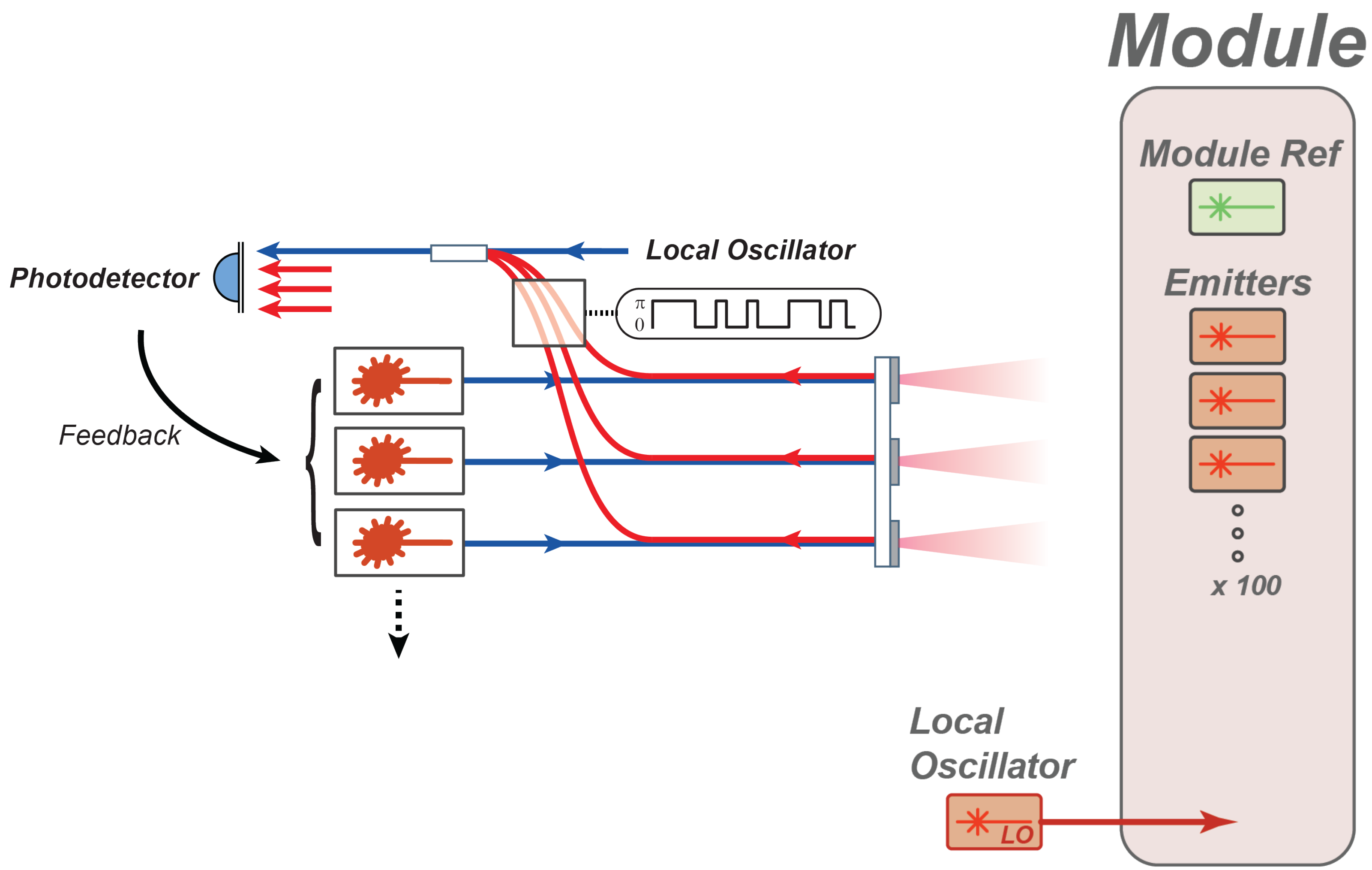


Two key concepts developed

1. Internally - A method to actively compare pathlengths between 10^8 emitters (give or take)
2. Externally - A method to measure the external pathlengths that deals with the expected large power disparity between the beacon and emitter lasers

C. P. Bandutunga, P. G. Sibley, M. J. Ireland and R. L. Ward, *Photonic solution to phase sensing and control for light-based interstellar propulsion. JOSA B, 2021. 38(5): p. 1477-1486.*

Hierarchical Optical Phased Array



Within a tier:

Phase comparison using code division multiplexing, Digital Inteferometry

Between tiers:

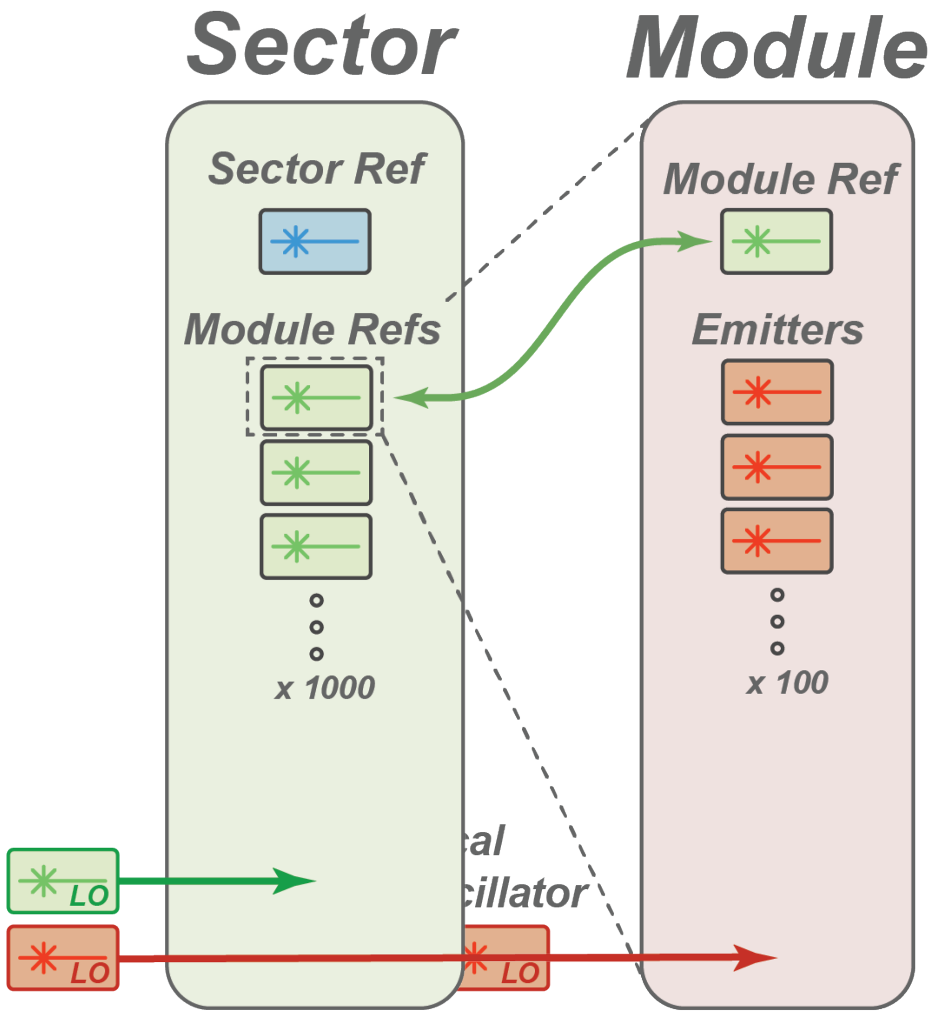
A wavelength offset reference separated by ~20-100 GHz links tiers to allow addition suppression of lower tiers

Size of a tier is limited by:

- Detector dynamic range (power saturation and shot-noise)
- Code division multiplexing crosstalk

Sibley. P.G., Scaling Optical Phased Arrays. 2021 – PhD Thesis

Hierarchical Optical Phased Array



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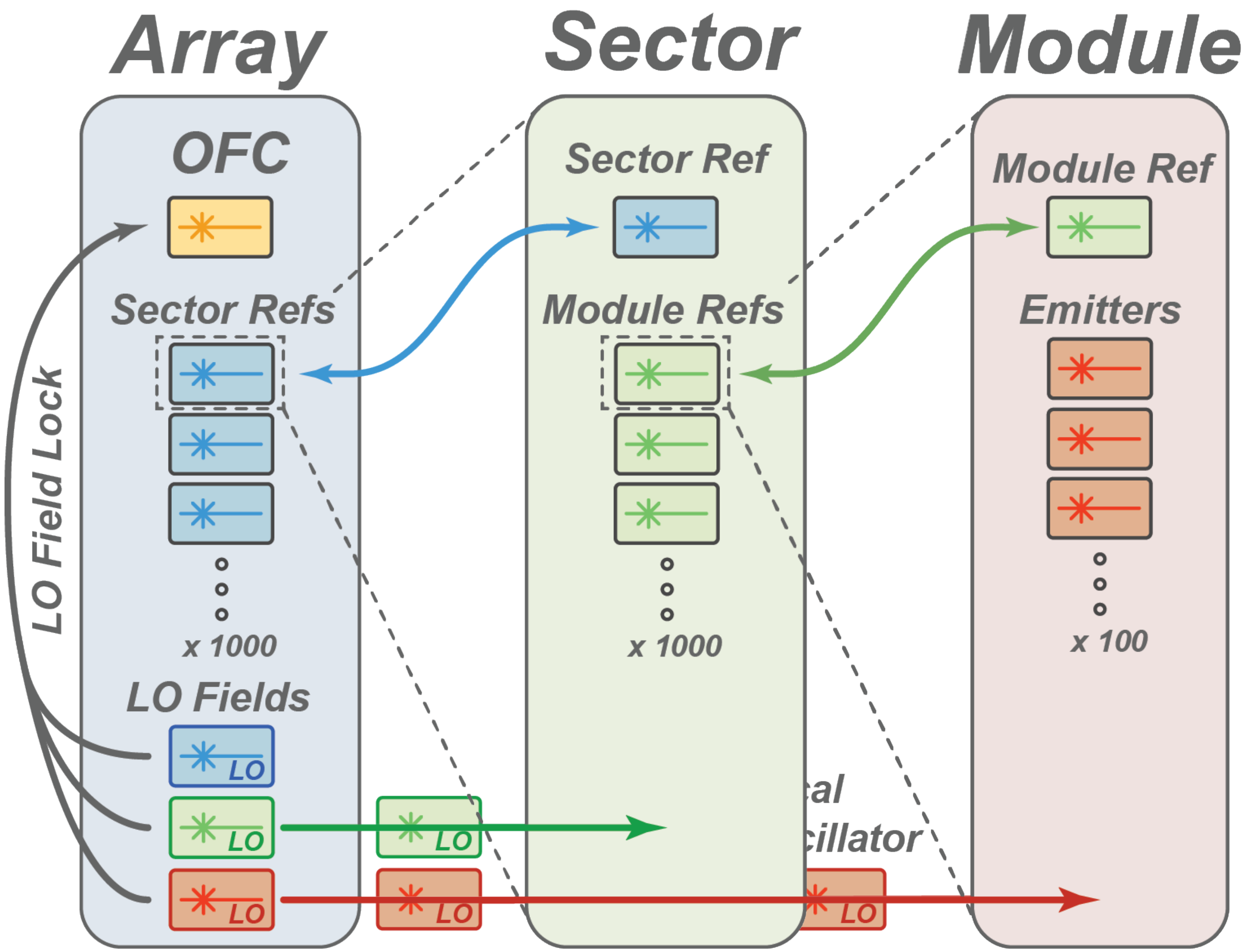
Hierarchical Optical Phased Array



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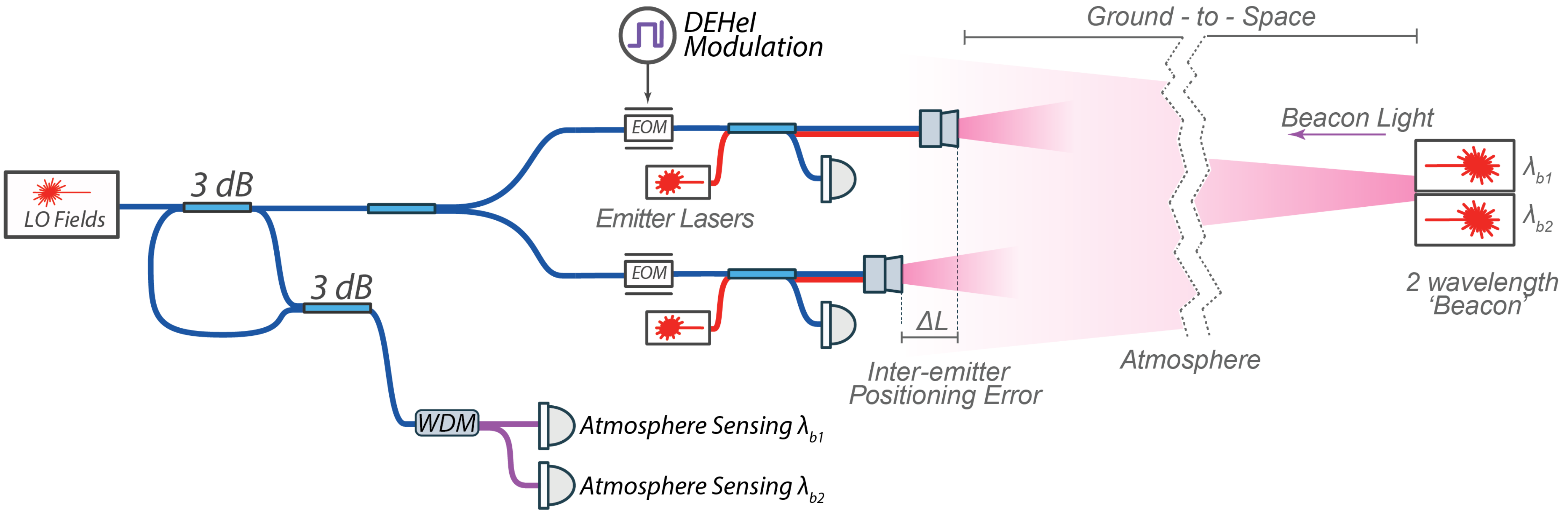
Sibley. P.G., Scaling Optical Phased Arrays. 2021 – PhD Thesis

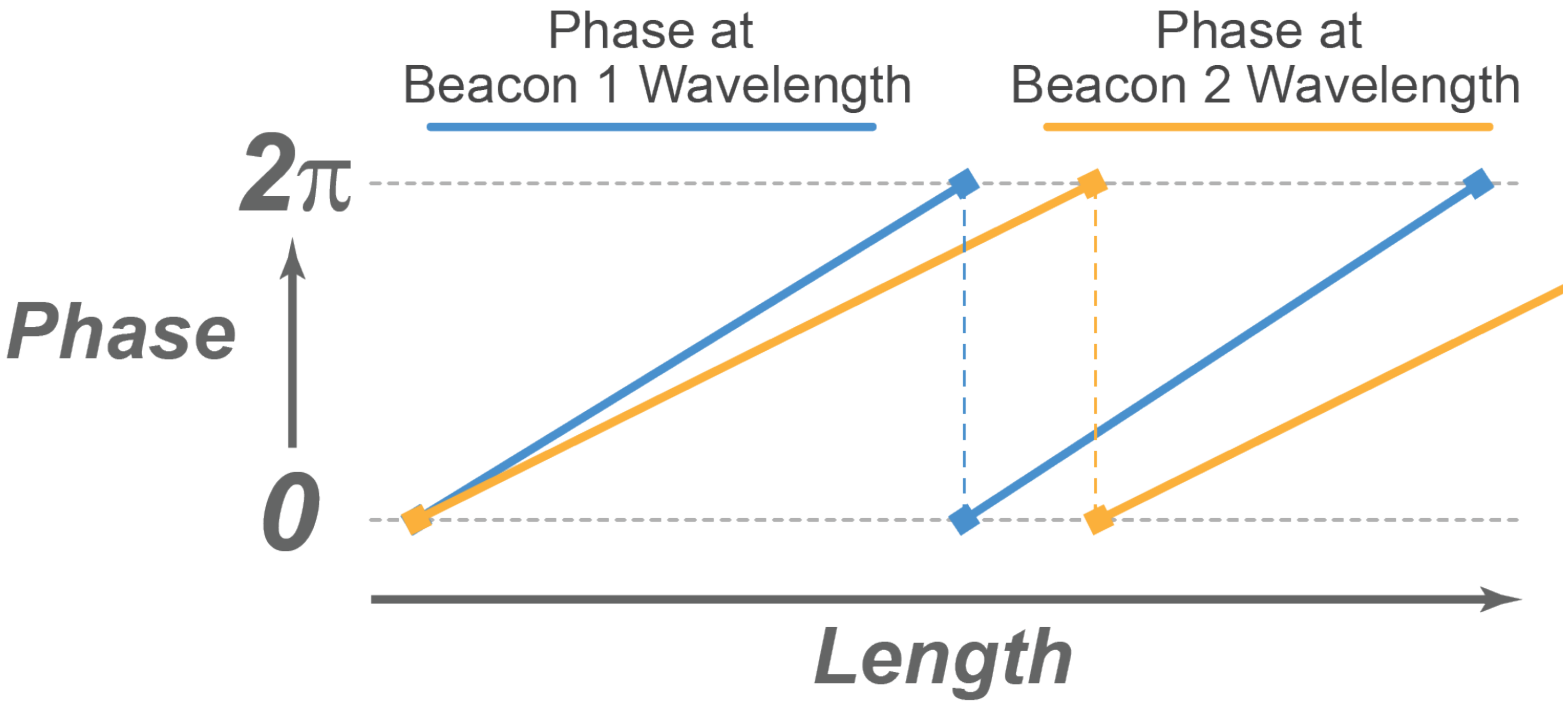
Beacon wavefront phase sensing



Optical power loss: ~80dB externally, ~50dB internally

Multi-wavelength phase sensing

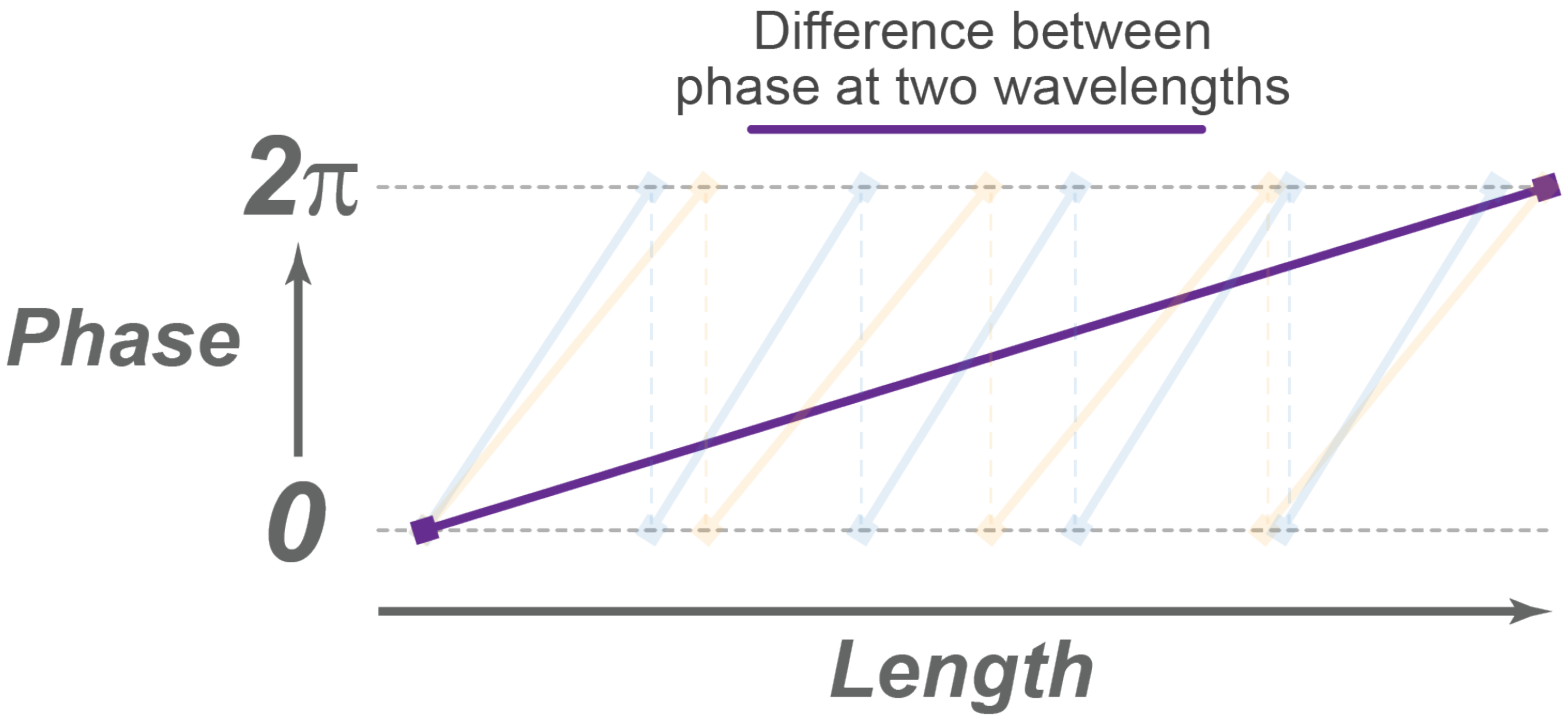
$$\text{Optical Phase} = \frac{\text{Optical pathlength}}{\text{Wavelength}}$$



Multi-wavelength phase sensing

$$\text{Optical Phase} = \frac{\text{Optical pathlength}}{\text{Wavelength}}$$

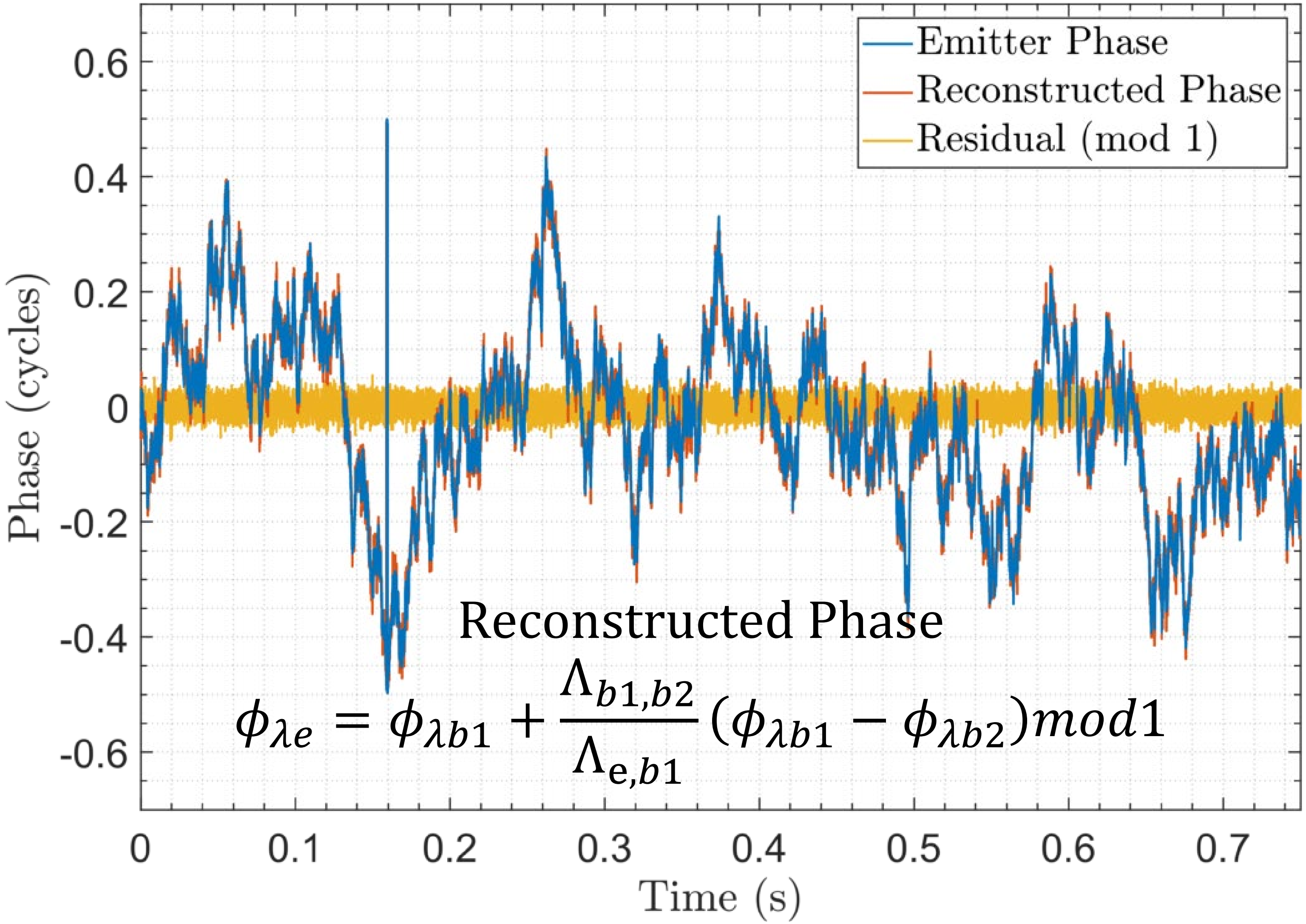
For a 100 GHz frequency shift, the synthetic wavelength is $\Lambda \approx 3$ mm



Using two wavelengths allows the length dependent phase error to be calculated

Specifically choosing these wavelengths significantly extends the unambiguous reconstruction range

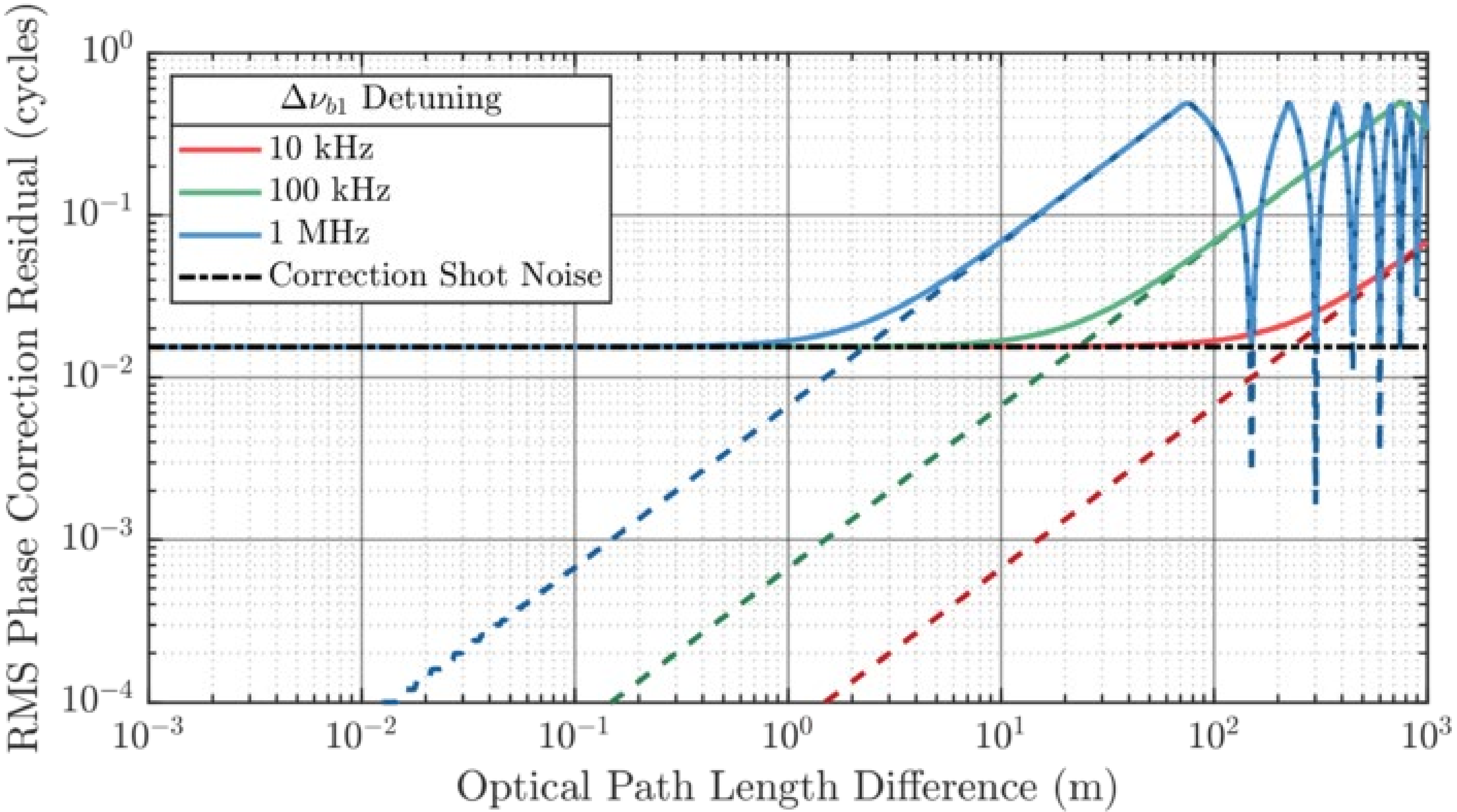
Simulated beacon phase measurement



Parameters:

- 10 cm length difference (with noise)
- Shot noise added for a 1 pW beacon (at detector)
- 10 kHz absolute frequency knowledge

Sensitivity to pathlength and wavelength differences



What's next?

Experimental proof of principles

- Begin proof-of-concept demonstrations

  Hierarchical structure

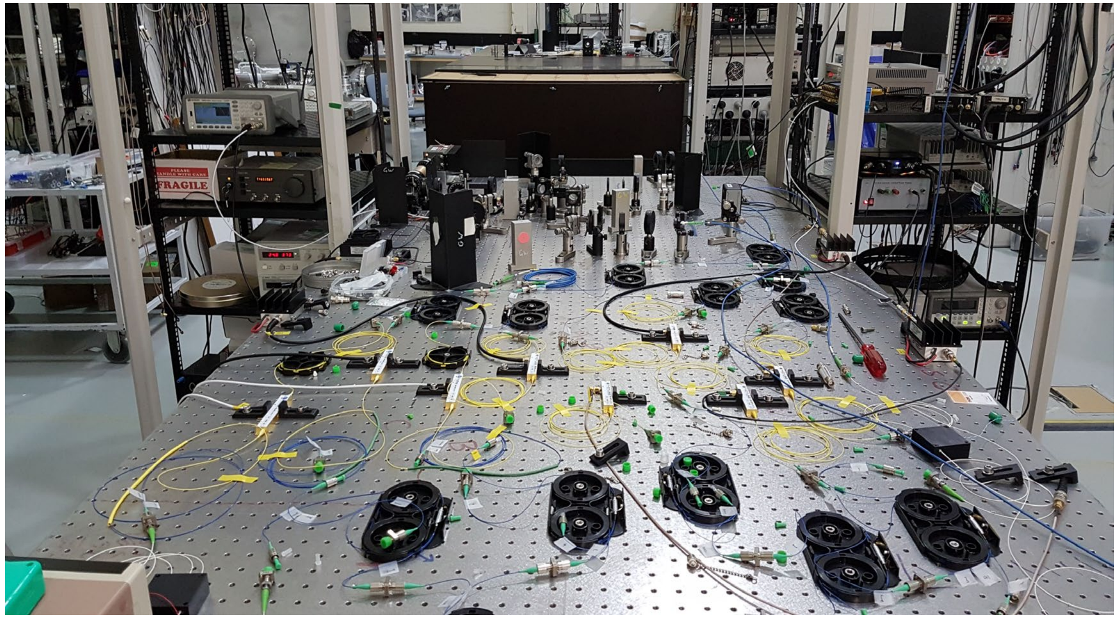
  Laser beacon-based wavefront sensing

  Multi-wavelength phase reconstructions/corrections

- Integration of advances in integrated photonics, laser technologies and new interferometric signal processing methods

Challenges for wider Breakthrough Starshot

- Cost
- Sailcraft development
- Communication



Contact Us

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paul.sibley@anu.edu.au

Image Credit: National Geographic

Additional *Concept System* Details

1000 channels is not 100,000,000

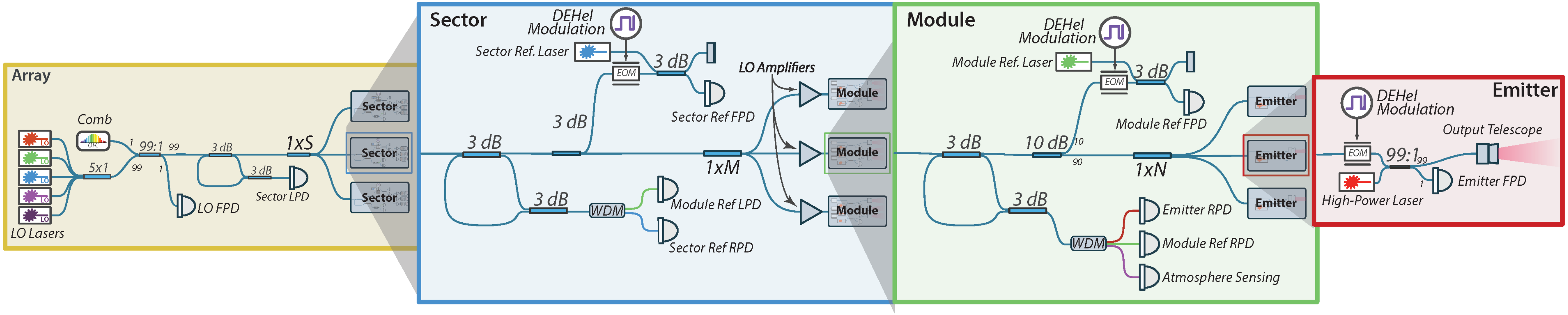
(this would need multi-THz sampling frequency)

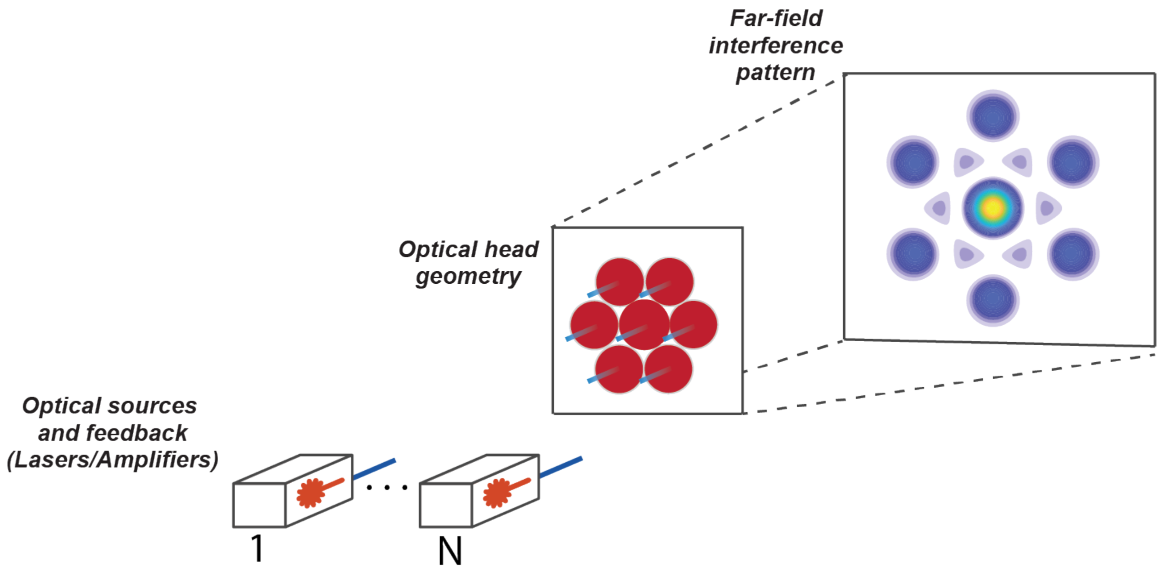
Sim

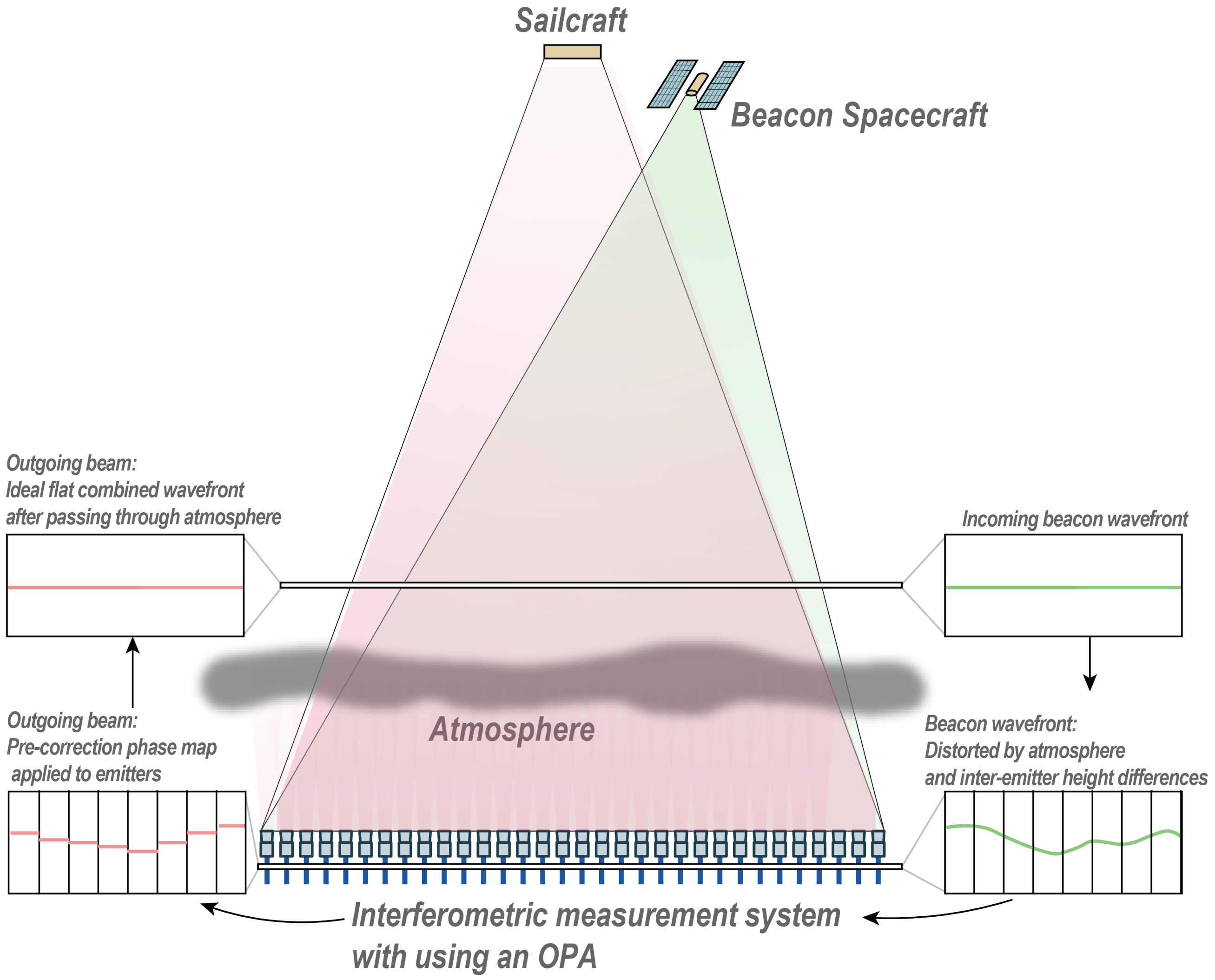
1. 656 MHz ADC
2. Phase readout rate 20 kHz
3. 1 kW individual emitters

Detection	λ_α	Phase
$\Phi_{FPD,e}[i,j,k]$	λ_e	$\phi A4_e + \phi A3_e[i] + \phi A2_e[i,j] + \phi A1_e[i,j,k] - \phi H1_e[i,j,k]$
$\Phi_{FPD,m}[i,j,R]$	λ_m	$\phi A4_m + \phi A3_m[i] + \phi A2_m[i,j] + \phi A1_m[i,j,R] - \phi H1_m[i,j,R]$
$\Phi_{RPD,e}[i,j,k]$	λ_e	$\phi A4_e + \phi A3_e[i] + \phi A2_e[i,j] + \phi LO1_e[i,j] - \phi H1_e[i,j,k] - 2\phi H2_e[i,j,k] - \phi A1_e[i,j,k] - \phi R1_e[i,j]$
$\Phi_{RPD,m}[i,j]$	λ_m	$\phi A4_m + \phi A3_m[i] + \phi A2_m[i,j] + \phi LO1_m[i,j] - \phi H1_m[i,j,R] - 2\phi H2_m[i,j,R] - \phi A1_m[i,j,R] - \phi R1_m[i,j]$
$\Phi_{FPD,s}[i,R,R]$	λ_s	$\phi A4_s + \phi A3_s[i] + \phi A2_s[i,R] - \phi H1_s[i,R,R]$
$\Phi_{LPD,m}[i,j,R]$	λ_m	$\phi A4_m + \phi A3_m[i] + \phi LO2_m[i] - \phi H1_m[i,j,R] - 2\phi H2_m[i,j,R] - \phi A1_m[i,j,R] - \phi A2_m[i,j] - \phi R2_m[i]$
$\Phi_{RPD,s}[i,R,R]$	λ_s	$\phi A4_s + \phi A3_s[i] + \phi LO2_s[i] - \phi H1_s[i,R,R] - 2\phi H2_s[i,R,R] - \phi A2_s[i,R] - \phi R2_s[i]$
$\Phi_{FPD,s}[R,R,R]$	λ_s	$\phi A4_s + \phi A3_s[R] - \phi H1_s[R,R,R]$
$\Phi_{LPD,s}[i,R,R]$	λ_s	$\phi A4_s + \phi LO3_s - \phi H1_s[i,R,R] - 2\phi H2_s[i,R,R] - \phi A2_s[i,R] - \phi A3_s[i] - \phi R3_s$
$\Phi_{RPD,s}[R,R,R]$	λ_s	$\phi A4_s + \phi LO3_s - \phi H1_s[R,R,R] - 2\phi H2_s[R,R,R] - \phi A3_s[R] - \phi R3_s$

Detailed Optical Layout

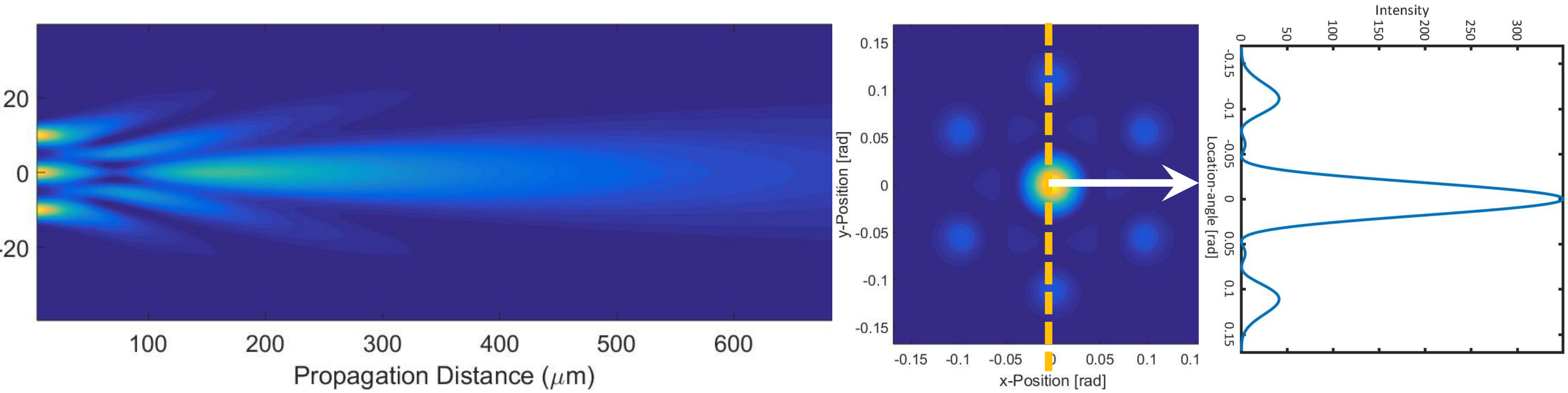



Far-field
interference
pattern
Optical head
geometry
Optical sources
and feedback
(Lasers/Amplifiers)
1
N


Sailcraft
Beacon Spacecraft
Outgoing beam:
Ideal flat combined wavefront
after passing through atmosphere
Incoming beacon wavefront
Atmosphere
Outgoing beam:
Pre-correction phase map
applied to emitters
Beacon wavefront:
Distorted by atmosphere
and inter-emitter height differences
Interferometric measurement system
with using an OPA

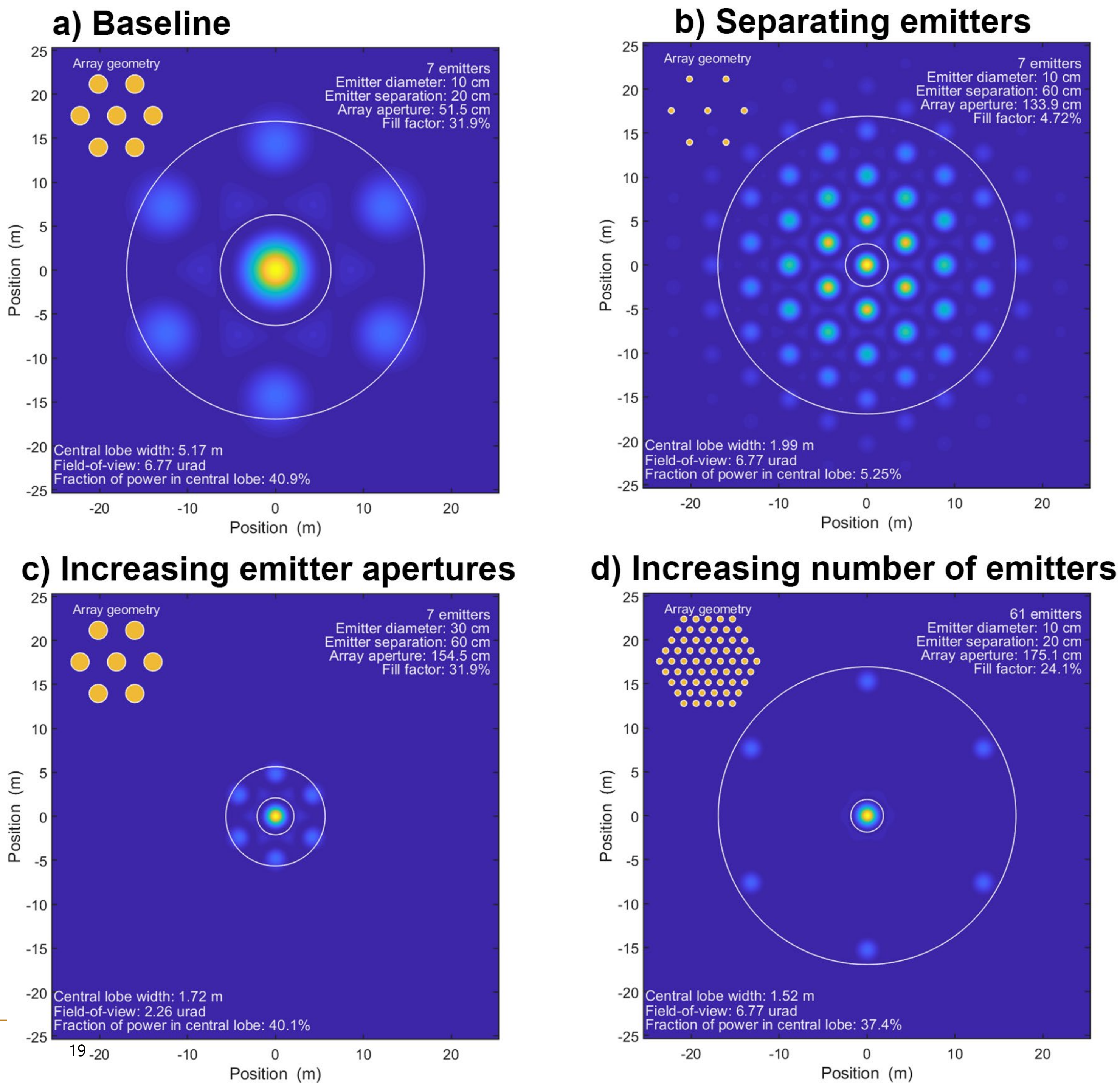
Far-field spatial interference

$$\sum_{i=1}^{N} \underbrace{\sqrt{P_i}\frac{W_0}{W(z)}}_{\text{Electric field amplitude}} \underbrace{e^{\frac{-\rho_i(x,y)^2}{W^2(z)} - ik\frac{\rho_i(x,y)^2}{2R(z)}}}_{\text{Wavefront curvature}} \underbrace{e^{ik(z+z_i(t)) - i(\omega t) + i\zeta(z)}}_{\text{Piston phase}}$$



Simulated beam intensity from 7 emitters in a hexagonal configuration and 10μm separation. From left to right: Cross section along the x-axis, Cross section along the z-axis (at z=1m), Cross section along the z and x axis)

Optical Head Geometry



- Can be predicted using the wavefront curvature term: $e^{\frac{-\rho_i(x,y)^2}{W^2(z)} - ik\frac{\rho_i(x,y)^2}{2R(z)}}$
- Different optical head geometries can result in vastly different output patterns
- $\rho_i(x,y) = \sqrt{(x-x_i)^2 + (y-y_i)^2}$
- Key parameters:
  - Central lobe width
  - Field of view and steering range
  - Power in the central lobe

Beacon Reconstruction Algorithm

$$\Lambda_{e,b1} = \frac{1}{\lambda_e} - \frac{1}{\lambda_{b1}} = \frac{c}{\Delta\nu_{b1}}$$

For a 100 GHz frequency shift, the synthetic wavelength is ~3 mm

Conversion using multiple beacons:

$$\phi_{\lambda e} = \phi_{\lambda b1} + \frac{\Lambda_{b1,b2}}{\Lambda_{e,b1}}(\phi_{\lambda b1} - \phi_{\lambda b2}) mod 1$$

Residual:

$$\frac{\Lambda_{b1,b2}}{\Lambda_{e,b1}}\left(\left\lfloor\frac{\Delta L}{\lambda_{b1}}\right\rfloor - \left\lfloor\frac{\Delta L}{\lambda_{b2}}\right\rfloor\right) mod\ 1$$

"Ideal" Condition:

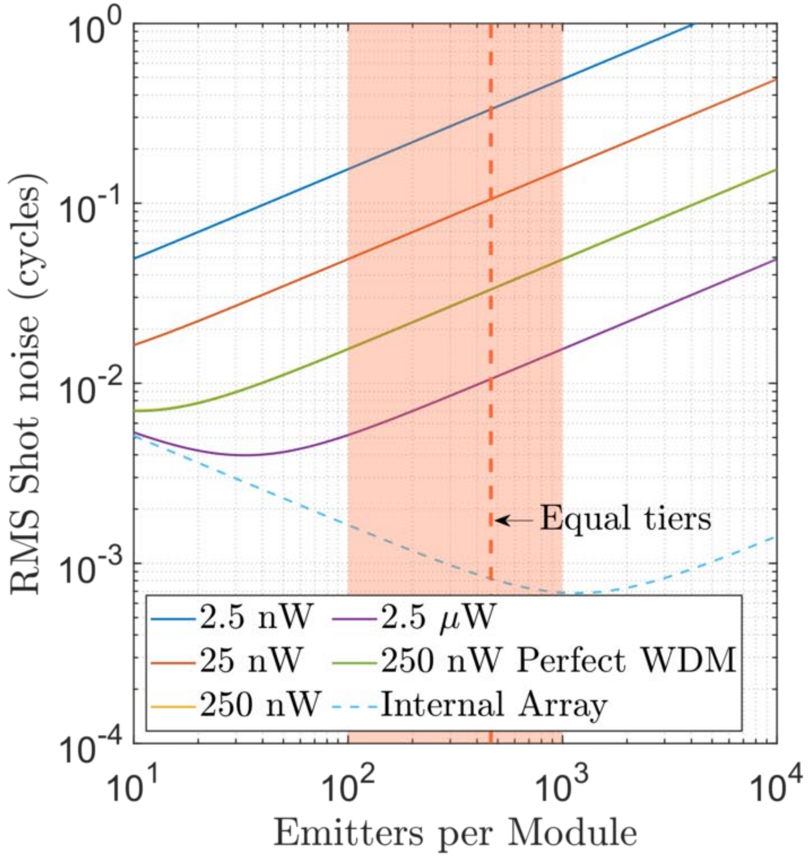
$$\Delta\nu_{b2} = \Delta\nu_{b1} + \frac{\Delta\nu_{b1}}{K}$$

$\Lambda_{e:b1} = \mathrm{K}\Lambda_{b1:b2}$ **(where K is an integer)**

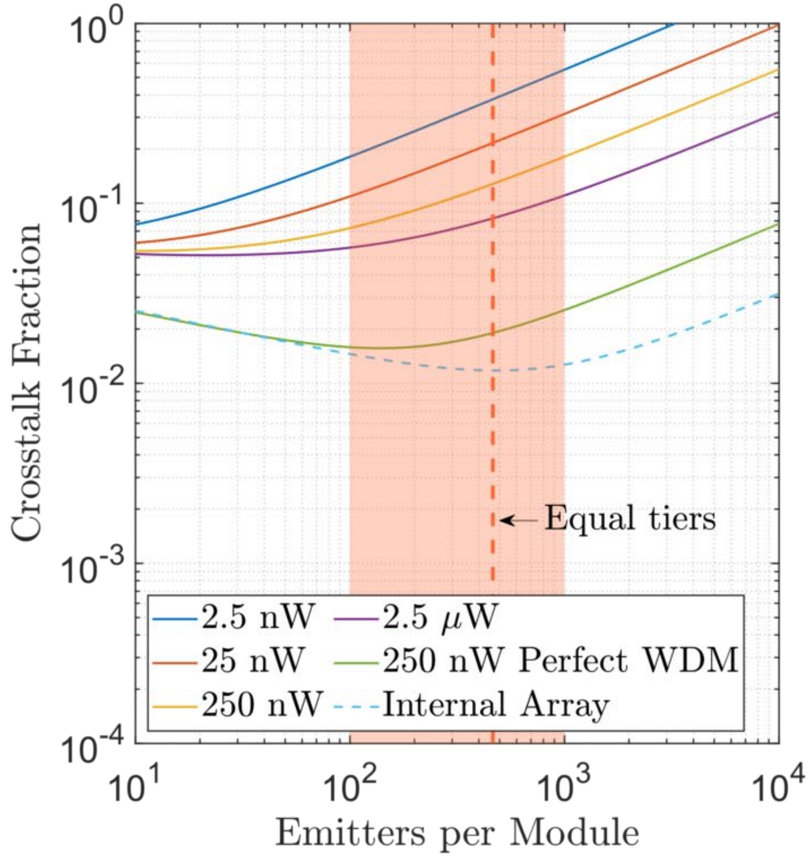
Predicted hierarchy OPA performance

Choosing parameters for the array

Shot noise

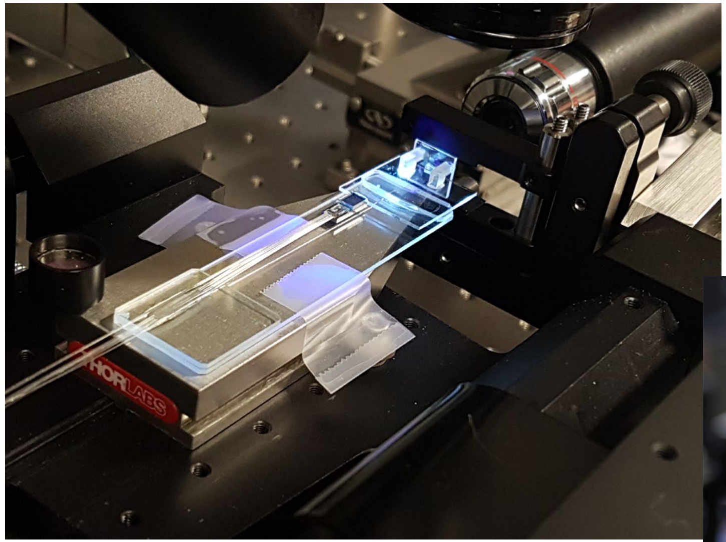


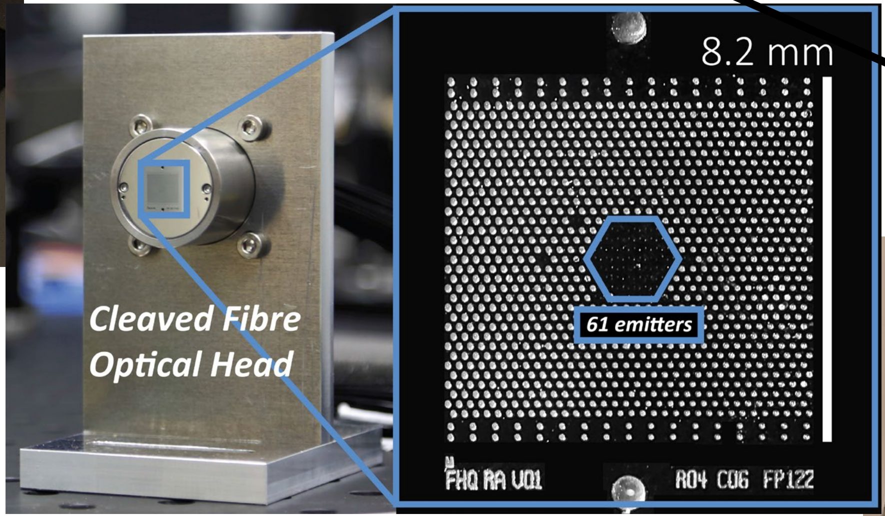
Crosstalk



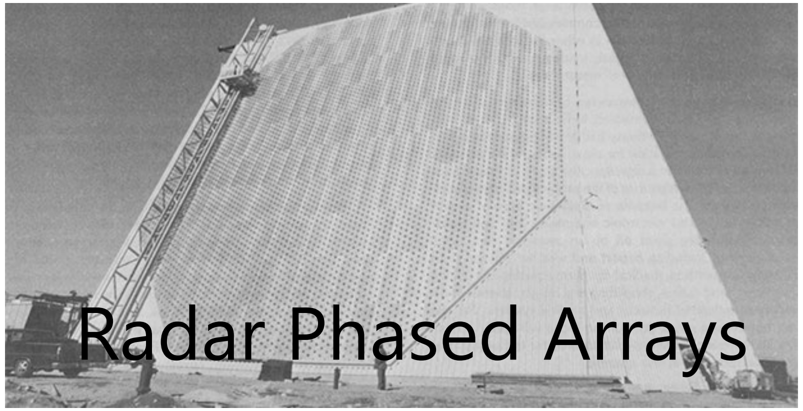
Different OPA Scales

Emitter Size





Roberts, L.E., *Internally Sensed Optical Phased Arrays*. 2016. – PhD Thesis


Radar Phased Arrays

https://www.iiviad.com/portfolio/fiber-array-technology/

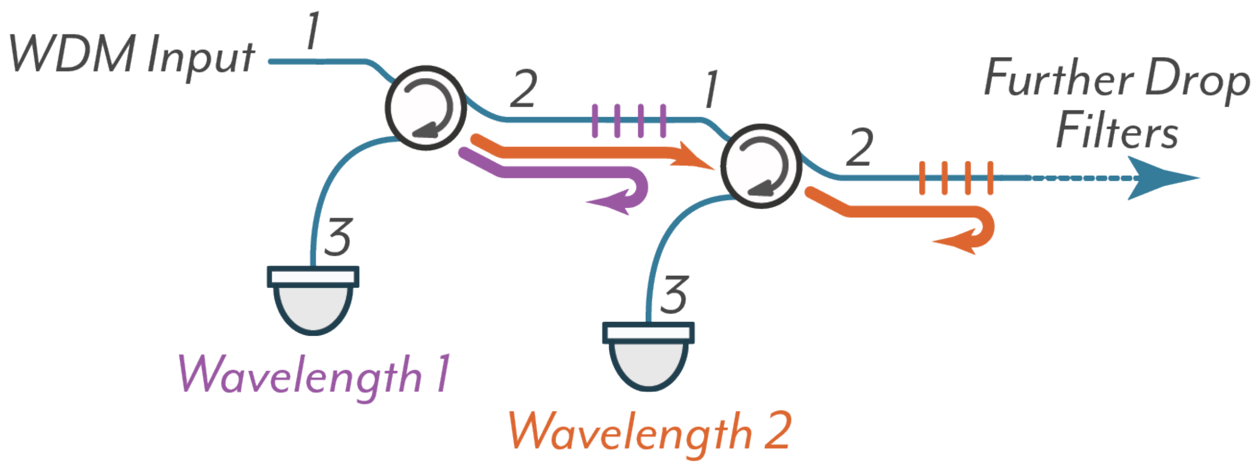
- Photonic integrated circuits
- Optical fibres / Microlens arrays
- Larger collimators

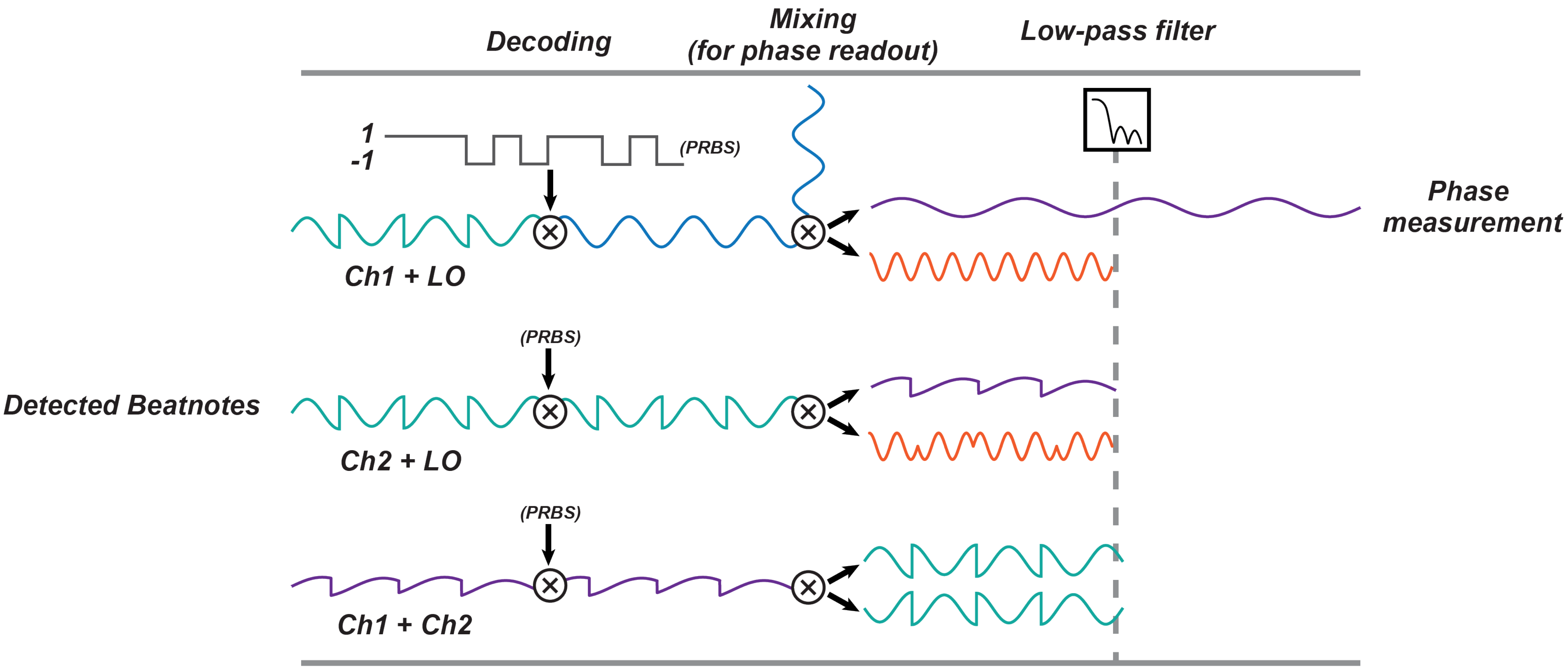
Wavelength multiplexed detector

Possible Solution:
Fibre Bragg gratings combined with optical circulators used to separate wavelengths.

DWDM communications readily achieve >20 dB channel isolation in the telecoms band with 100 GHz channel spacing

Proposed topology allows for a worst case 20 dB isolation with 100 GHz wavelength separation





Decoding
Mixing
(for phase readout)
Low-pass filter
1
-1
(PRBS)
Phase
measurement
Ch1 + LO
(PRBS)
Detected Beatnotes
Ch2 + LO
(PRBS)
Ch1 + Ch2